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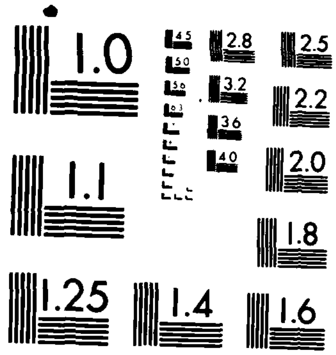

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Aero Propulsion Technical Memorandum 427

A PRELIMINARY EVALUATION OF SOME GEAR DIAGNOSTICS USING VIBRATION ANALYSIS

by

S.C. FAVALORO

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SUMMARY

Several condition monitoring methods for gears, which utilise the signal average of gear vibration in both the time and frequency domain, have been investigated during a 1500 hour test on a gear rig.

Results have shown that although heavy wear, in the form of fine pitting and scuffing, occurred over most of the tooth surfaces, the time domain procedures and levels of the fundamental and first harmonic of meshing frequency did not respond to damage to the gears. Total vibration level and the ratio of sideband to total energy showed only marginal response to wear.

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CONTENTS

Ideally, the signal/noise ratio is improved by a factor of $\sqrt{N}$ when N records are averaged. In practical situations the improvement is limited by problems such as "tacho-jitter" (initial phase error) or a lack of synchronicity and as a result, correlation methods can be employed to determine when the average has stabilised (i.e. to maximise the signal/noise ratio).

3. SIGNAL ANALYSIS METHODS

Analysis methods described in this paper can be classified into those that operate on the signal average in the time domain and those which transform the signal into the frequency domain.

3.1 Time Domain Methods

Time domain procedures have their basis in probability theory and most time domain discriminants are derived from the probability density curve. Stewart (2) lists a range of discriminants, or figures of merit FMn, which he claims to be effective in the detection and diagnosis of gear damage. Two of these discriminants, FMØ & FM4 in Stewart's terminology, are examined in this paper.

FMØ is defined as peak-to-peak level of the signal average divided by the rms level of the meshing frequency components. Like the standard peak/rms ratio (crest factor) FMØ provides a simple measure of changes in the signal pattern. Faults such as tooth breakage, which may increase peak-to-peak height but not greatly effect meshing frequency levels, and heavy wear, which generally has no appreciable effect on peak-to-peak but tends to reduce meshing frequency levels, should be detected using FMØ. Response of FMØ to minor tooth damage would be limited as neither peak-to-peak height or meshing frequency level would be greatly affected.

However, damage to a single tooth will produce a change in the vibration pattern and FM4 has been designed to respond to this change. The principle behind FM4 is the removal of regular, or meshing, components from the average and computing the standard deviation and kurtosis of the remainder, or difference signal. The standard deviation (rms level) of the remainder indicates the energy contribution of non-meshing components while kurtosis essentially indicates the occurrence of peaks in the signal. For a gear in good condition, the difference should be essentially noise with a Gaussian amplitude distribution and a kurtosis value of three. The rms level of the difference should be low relative to the original signal. Spalling or cracking in a single tooth modulates the meshing pattern when the tooth goes into mesh, and this modulation should appear as a peak, or series of peaks in the difference. Kurtosis of the difference would then increase, and if the modulation is severe, the rms level would also increase.

One problem associated with FM4 is to determine the regular components in the average. Stewart (2) favours the removal of meshing frequency components and their immediate sidebands as well as all shaft order harmonics and their sidebands. This procedure has been used in the following tests, even though it may entail the removal of some fault induced irregularities.

1. INTRODUCTION

Several experimental rigs have been in use for some time for the purpose of evaluating condition monitoring methods for gears. While the major thrust of the experimental programme has been directed towards oil borne wear debris analysis, a concurrent programme has been initiated to investigate some vibration analysis techniques which may be suitable for the condition monitoring of gears.

Traditional vibration analysis methods for gears utilise spectrum analysis since distinct meshing frequency components and associated harmonics and modulation sidebands are readily identified. Deterioration or damage to the gears can be determined by comparison of current spectra with 'baseline' spectra taken when the gears are known to be in good condition. Although such methods are proven, they are limited in that changes in the amplitudes of meshing components can be due to changes in the load on the gears, and as such, operating conditions must be the same if a valid comparison of spectra is to be made.

Pattern recognition methods on the other hand need no recourse to historical information since the vibration signal forms its own reference. In addition, vibration patterns are normally independent of operating conditions so reproducing identical test conditions for comparison of records becomes less critical.

This paper examines some of these analysis methods and presents results obtained from preliminary experiments. The starting point for all methods described is the signal average.

2. SIGNAL AVERAGING

In a machine comprising a large number of working components the signal detected by a vibration sensor is complex, since it is made up of a combination of signals from different sources arriving at the sensor through various transmission paths in the machine. When attempting to study the vibration from a particular component, the signal can be disguised by signals from other components. Limited enhancement of the component signal can be achieved by strategic location of the vibration sensors, but in general the removal of unwanted signal components, or noise, is part of the signal analysis task. (1)

Signal averaging, or summation, is the commonest way of enhancing a coherent signal which is concealed in noise. The process is an ensemble average, where components periodic in the ensemble interval are reinforced while random noise and signals with other periodicity tend to cancel out. The process is particularly applicable to gearboxes, as averaging synchronised with one gear by a trigger signal from the rotating shaft will tend to cancel vibration from non-synchronous gears as well as other noise sources such as bearings.

3.2 Frequency Domain Methods

As with the time domain methods, the starting point for analysis in the frequency domain is the signal average. The average is transformed into the frequency domain using the Fast Fourier Transform (FFT) and a number of parameters from the spectrum are plotted against time.

The parameters which have been investigated are the total rms vibration level of the average, the rms vibration levels in the fundamental and second harmonic of meshing frequency and the ratio of the vibration level in the first order sidebands to the total vibration level. Early investigations showed that for the gearbox used in the experiments and with the gears in good condition the majority of vibration energy is contained in the fundamental and second harmonic of meshing frequency. Hence, changes in the level of these components and the total vibration level can indicate major changes in the meshing action of the gears, while changes in the first order sideband level/total level ratio can indicate damage to a single tooth or the gear shaft.

4. EXPERIMENT

4.1 Test Rig

Figure 1 shows the rig used in the tests; it consists of two gearboxes arranged in a back to back configuration, each containing three spur gears. The gearbox at the rear contains an idler gear which is loaded by the lever arm, and transmits torque to the test gears shown in the front of the figure. The test gears A and C, each have 38 teeth and mesh with an idler gear which has 37 teeth. The nominal running speed is 3000 R.P.M., or 50 Hz, and so the meshing frequency of the test gears is 1900 Hz. Lubrication of the test gears is by splash feed from a sump which is isolated from the bearings and other gearbox to prevent oil contamination.

4.2 Instrumentation

Figure 2 shows a block illustration of the instrumentation used to construct the signal average. The Kistler accelerometers have a nominal resonance of 34 kHz and sensitivity of 9.9 mV/g and are mounted adjacent to each test gear (i.e. on the relevant bearing housing) as shown in Figure 1. Mounting the transducers as close as possible to each gear will reduce the effect of interference from the other gear on the vibration signal.

The Rockland 452 Hi/lo filter is set at 20 kHz low pass and cascading both channels gives a roll off of 48 db/octave. Since the rotational speed of the gears can vary, a Spectral Dynamics SD 134A tracking ratio tuner has been used to provide synchronous averaging.

The Biomation 1010 waveform recorder is a digital recorder with a storage capacity of 4000 10 bit words. The filtered vibration signal is digitised on the Biomation and with the multiply/divide ratio of the SD 134A set to 1600:1, the signal from one complete revolution of the test gear occupies 1600 words on the Biomation.

The vibration data from two gear revolutions (3200 words) comprises one record and is passed to the VT 103 computer on the IEEE bus. The Biomation is coupled to the IEEE bus by an ICS 4880 interface.

4.3 Numerical Computations

4.3.1 Signal Average

The signal average $\bar{x}$ (t) of N records of the raw vibration signal x (t) is given by -

$$\bar{x}\ (t) = \frac{1}{N} \sum_{n=0}^{N-1} x\ (t + nT) \qquad (1)$$

where T = coherence time, or time for one gear revolution

N = number of records averaged.

The signal average is assumed to be stable when the correlation coefficient between averages N and N/2 is greater than 0.99. The correlation coefficient r is given by -

$$r = \frac{\sum_{i=1}^{n} (\bar{x}_{i,N})\ (\bar{x}_{i,\ N/2})}{\sqrt{\sum_{i=1}^{n} (\bar{x}_{i,N})^2 \sum_{i=1}^{n} (\bar{x}_{i,\ N/2})^2}} \qquad (2)$$

where n = total number of data points in a record.

4.3.2 FMØ (Figure of Merit, Ø)

FMØ of the signal average $\bar{x}$ (t) is given by -

$$FM\emptyset = \frac{\bar{x}_{\text{peak-to-peak}}}{\bar{x}_{HRMS}} \qquad (3)$$

where $\bar{x}_{HRMS}$ = rms level of meshing frequency components.

Peak-to-peak level calculated from the signal average represents the average of the peak-to-peak levels which exceed the 0.99 quantile.

4.3.3 FM4 (Bootstrap Construction)

Using the signal average, the three main steps in this procedure are as follows:

(1) Discrete Fourier Transform of the average:

$$\bar{x}\ (t) \xrightarrow{\text{DFT}} \bar{X}\ (\omega)$$

(2) Formation of regular components, $H(\omega)$ and inverse transform:

$$H\ (\omega)\ = f\left[\bar{X}\ (\omega)\right] \xrightarrow{\text{IFT}} h\ (t)$$

where $H\ (\omega)$ = the first ten (10) meshing frequency harmonics and their immediate (1st order) sidebands.

(3) Construction of the difference file, $d(t)$ -

$$d(t)\ =\ \bar{x}\ (t)\ -\ h\ (t)$$

Two operations are then performed with the difference file, $d(t)$ -

(i) Standard Deviation Ratio, SDR $= \dfrac{\text{S.D.}\left[d\ (t)\right]}{\text{S.D.}\left[\bar{x}\ (t)\right]}$

(ii) Kurtosis of the difference file,

$$K\left[d\ (t)\right] = \frac{n \sum_{i=1}^{n} (d_i - \bar{d})^4}{\left[\sum_{i=1}^{n} (d_i - \bar{d})^2\right]^2}$$

where n = number of data points

$$\text{and} \qquad \bar{d} = \frac{1}{n} \left(\sum_{i=1}^{n} d_i \right)$$

SDR and $K\left[d(t)\right]$ constitute FM4

5. RESULTS AND DISCUSSION

The load profile used in the test was set to suit the requirements of the wear analysis programme and is shown in Figure 3(a). The cumulative weight loss from test gears A and C is shown in Figure 3(b). Trends of the total vibration level for both gears is shown in Figure 4.

Figure 5 shows a typical time domain analysis. Figure 5(a) shows the signal average for one revolution of gear C, Figure 5(b) shows the regular components of the average, h(t) and Figure 5 (c) is the difference signal, d(t). Figure 6 shows the spectrum of the signal average with absolute vibration level as the ordinate in Figure 6(a) and decibel, referred to the maximum vibration level, as the ordinate in Figure 6(b). The time domain results, FMØ and FM4 are shown for both gears in Figures 7 and 8 respectively.

In the frequency domain, trends of the vibration levels in the fundamental and second harmonic components of meshing frequency are shown in Figures 9 and 10 respectively, and the ratio of first order sideband energy to total energy is shown in Figure 11.

5.1 Gear Wear

Examination of the gears during and at the conclusion of the test showed pitting and scuffing as the principal gear wear mechanisms. The pitting, although fine, occurred over most of the tooth surfaces and the extensive plastic deformation evident was characteristic of scuffing (3). No major spalls or cracking were evident on either of the gears. The most severe wear occurred on both gears during the final 85 hours when the tooth load was very high (Fig. 3); but the preceding 400 hours is perhaps the most useful for vibration analysis since during this period substantial wear occurred on gear C (and to a lesser extent on gear A) while the tooth load remained constant. (Fig. 3). The difference in the wear rate is difficult to explain, since both gears were manufactured under identical conditions and meshed with the same gear.

5.2 Total Vibration Level (Figure 4)

Changes in level for both gears over the first 900 hours could be attributed to changes in the tooth load, since wear on the gears was at a minimum. The following 460 hours (900 to 1360) saw a clear increase in level for gear C, and to a lesser extent for gear A. Since the load was constant during this period, this increase can be attributed to increasing gear wear. The final 85 hours saw a rapid increase in level for both gears - the source of which is most likely the combination of the increased load and wear on the gears.

5.3 FMØ and FM4 Analysis (Figures 7 and 8)

After some variation between 4.0 & 5.0 over the first 600 hours of the test, FMØ for both gears settled down to a value of approx. 4.0 for the remaining 850 hours. With the type of wear suffered by the gears the latter result is surprising, since it was envisaged that although the peak-to-peak height of the average would not alter greatly, the increasing wear on the gears, especially gear C, may channel more of the total vibration energy into non-regular components, thereby reducing the harmonic contribution to the total, and causing an increase in FMØ value.

FM4 for both gears followed a similar pattern to FMØ - namely, some variation in the first 600 hours (S.D.R. from .2 to .3, kurtosis from 2.8 to 3.2 for gear A, and S.D.R. from .25 to .38, kurtosis from 2.8 to 3.0 for gear C) and then settling down to reasonably constant values over the remaining 850 hours (S.D.R. from .13 to .19, kurtosis 2.7 to 3.3 for gear A, and S.D.R. from .15 to .3, kurtosis from 2.9 to 3.1 for gear C). The absence of any kurtosis values greater than 3.5 indicates a lack of any peaks in the difference file. Considering the type of wear the gears suffered (i.e. no individual tooth damage), this can be expected. It should be emphasised that extensive damage to a single tooth would produce modulation sidebands at the fundamental and harmonic meshing frequencies, spaced at orders of the shaft frequency - these sidebands are removed in the regular reconstruction of the average.

The relatively constant values for S.D.R. indicate that the contribution of non-regular components to the total signal level is not increasing with increasing wear. In essence, this confirms the reason for constant FMØ values, i.e. the contribution of regular, or harmonic, components and non-regular components to the total signal level are staying in the same ratio.

5.4 Frequency Domain Analysis

5.4.1 Levels

Trends of the vibration level at the fundamental and first harmonic of meshing frequency for both gears present a reasonably straightforward picture (Figures 9 & 10). Increases in levels tend to match increases in the applied tooth load. The drop in the fundamental level between 600 and 1060 hours and the variation in level between 1060 & 1360 hours for gear A (Figure 9) are not readily explained - but it would seem that wear has minimal effect on the fundamental level as evidenced by the relatively constant values obtained for gear C during this period (1060-1360 hrs)

when the wear rate was high (Fig 3(b)). Similarly, the second harmonic does not appear to be influenced by the type of wear the gears suffered.

5.4.2 Ratios

The ratio of sideband to total energy varies in a complex manner for both gears (Fig 11). The fall in level at 375 hours for both gears corresponds to the fall in FMØ & SDR (Figs 7 & 8). Since virtually no wear occurred in the period 250 → 500 hrs (Fig 3(b)) and no change registered in any of the other parameters, the fall in level does not seem to be related to gear wear.

In a similar manner, the variation in ratio for gear A over the final 400 hours of the test is difficult to correlate with any wear. However, the rise in ratio at 1260 hours for gear C, when considered with a corresponding rise in SDR (Fig 8) indicates some change in the meshing action, since the total vibration level (Fig 4) rises but the harmonic components remain steady (Figs 9 & 10). This change in the mesh can be attributed to the heavy wear on gear C. The fall in ratio from 1350 hours onwards is caused by the increased load on the gears and subsequent increase in the levels of the fundamental and harmonic components.

6. CONCLUSIONS

In a 1500 hour test on a back-to-back gear rig, during which the tooth load was progressively increased and heavy pitting and scuffing occurred on the tooth surfaces, several condition monitoring methods using vibration analysis were investigated. All methods analysed used the signal average of the gear vibrations, either transforming the average into the frequency domain or computing discriminants directly in the time domain.

The time domain parameters, FMØ and FM4, were of little effect in detecting wear to the gears, and did not change with increases in the applied load. In the frequency domain, trends of the vibration level of the fundamental and second harmonic of meshing frequency showed no response to wear and only increased as the applied load increased. Total vibration level was found to respond to heavy wear and applied load while the ratio of sideband to total energy showed only marginal response to heavy wear.

It is reasonable to assume that the type of wear suffered by the gears is associated with the lack of response of the discriminants investigated, since fine and uniform pitting over the whole of the tooth surfaces may not affect the structural integrity of the gears and hence cause only minor changes to the meshing pattern. Another reason could be that the meshing frequency of both test gears was identical, and indeed was the same as the meshing frequency in the driving gearbox. Hence, there is a possibility that the signal average recorded for each test gear was interfered with by vibration from the other gears in the system, even though attempts were made to minimise this effect by careful location of the transducers.

Further tests with discrete spalls or cracks introduced into one or several gear teeth and testing on a gearbox where the meshing frequencies are not identical with each other would clarify the value of the methods investigated.

REFERENCES

(1) Swansson, N.S.(1980) "Application of Vibration Signal Analysis Techniques to Condition Monitoring", Conference on Lubration, Friction and Wear in Engineering, 1980, Melbourne.

(2) Stewart, R.M. (1979), "MOD Presentation, Technical Brochure", Machinery Health Monitoring Group, ISVR, University of Southampton.

(3) Atkin, M.L. (1984), "Australian Progress Report 1984, TTCP-PAG7 Meeting, USA, July 1984.

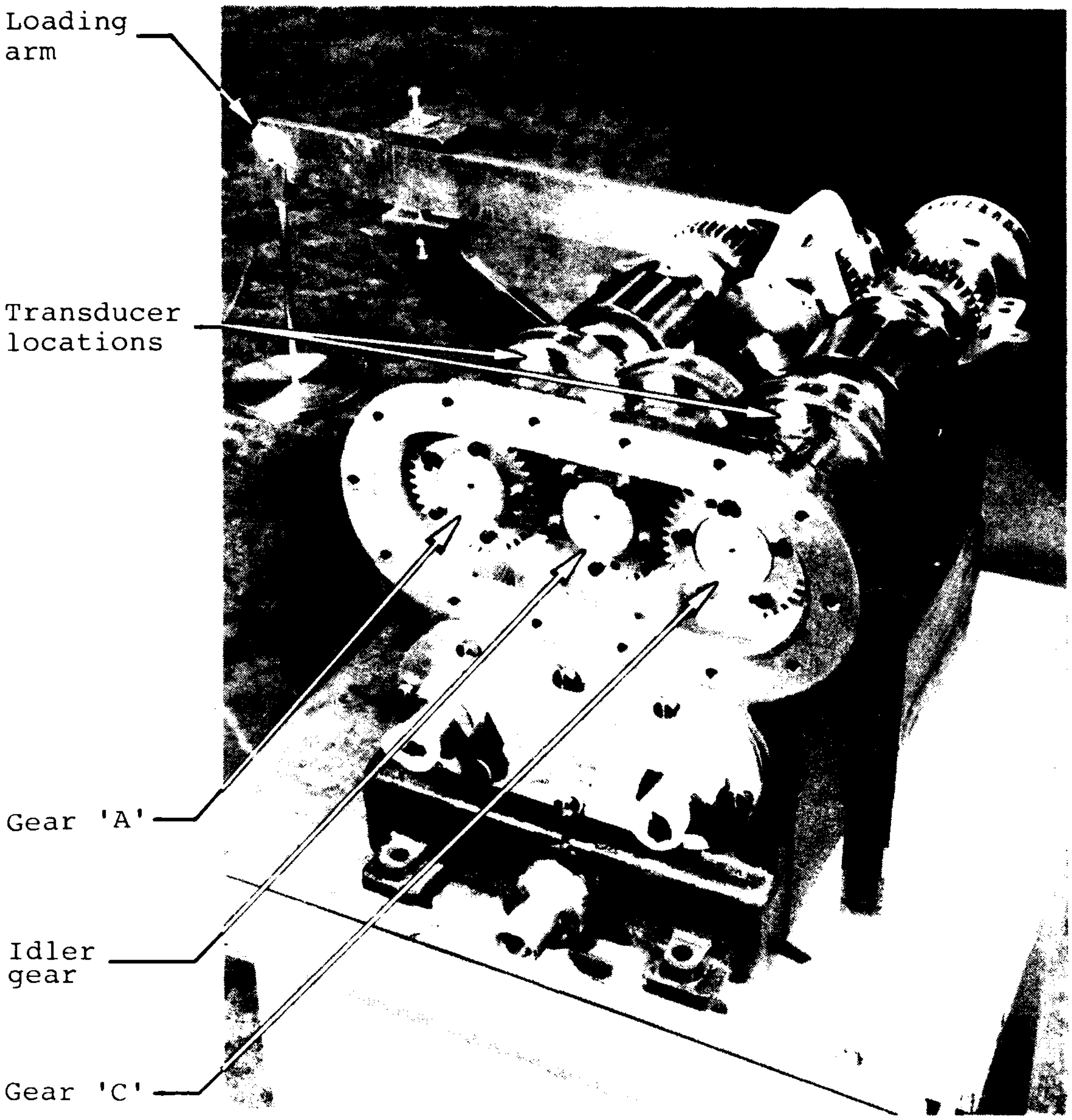


FIG 1. MARK II GEAR RIG

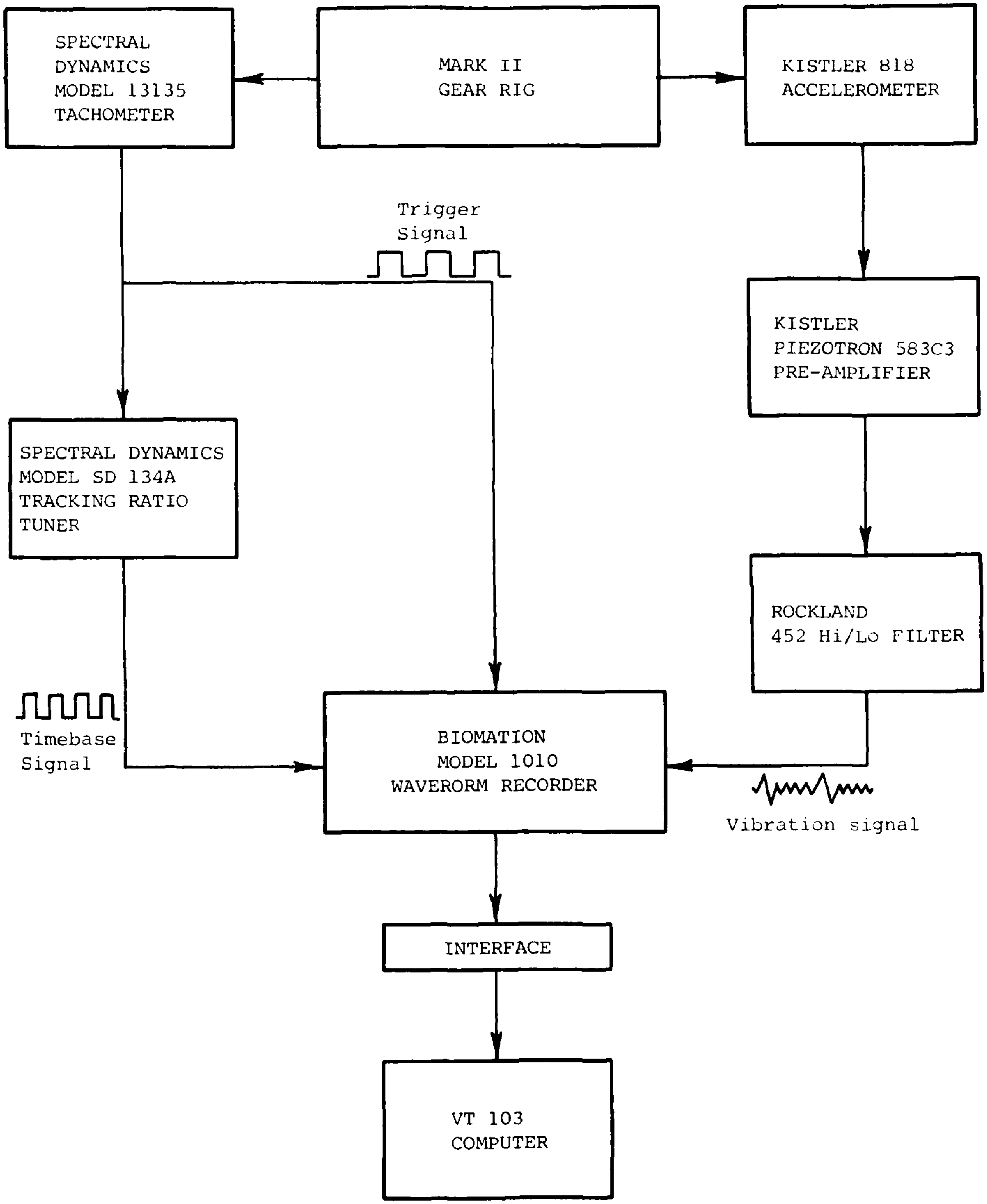


FIG 2. INSTRUMENTATION

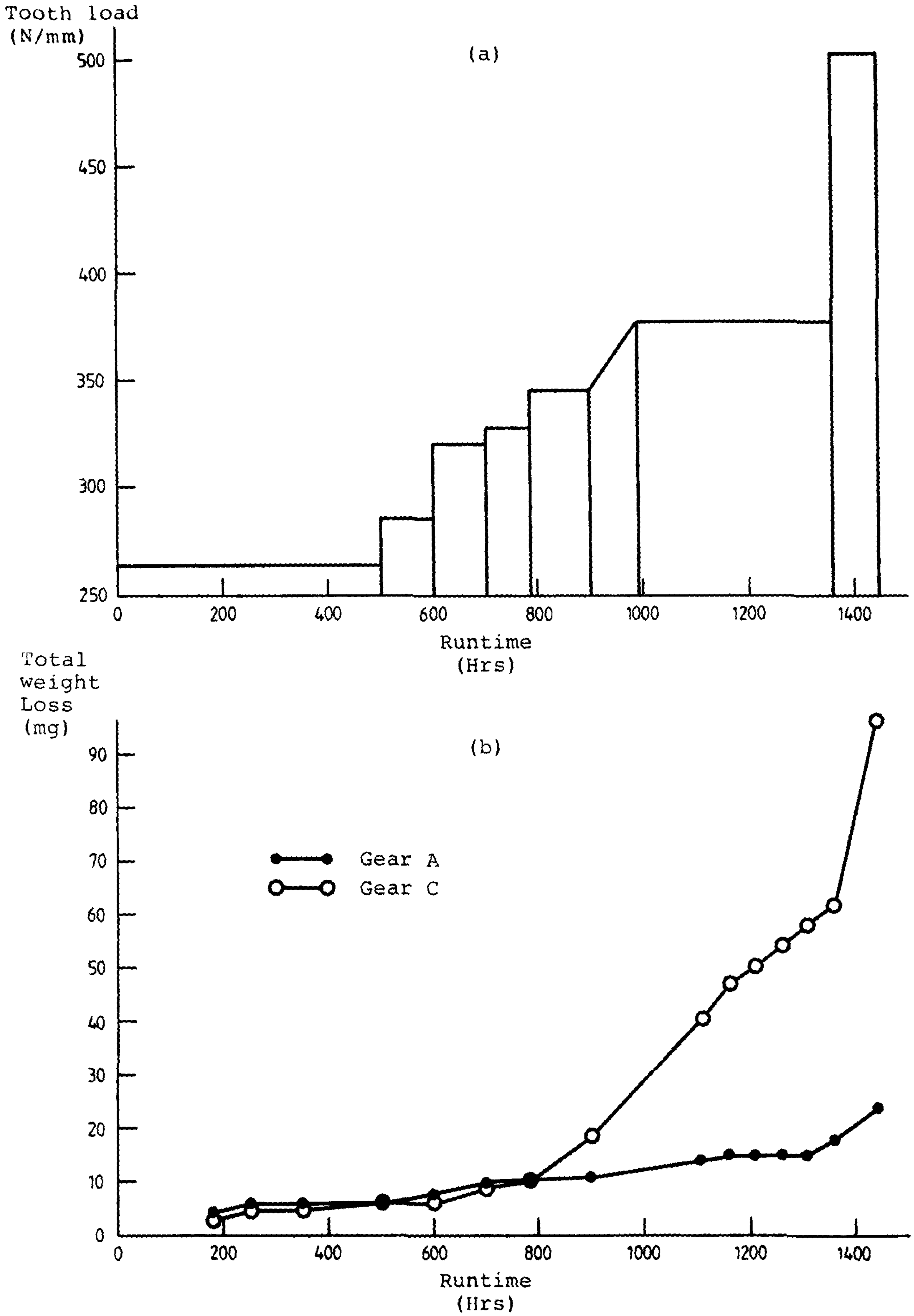

Tooth load
(N/mm)
(a)
500
450
400
350
300
250
0
200
400
600
800
1000
1200
1400
Runtime
(Hrs)
Total
weight
Loss
(mg)
(b)
90
80
70
60
50
40
30
20
10
0
Gear A
Gear C
0
200
400
600
800
1000
1200
1400
Runtime
(Hrs)

FIG 3.

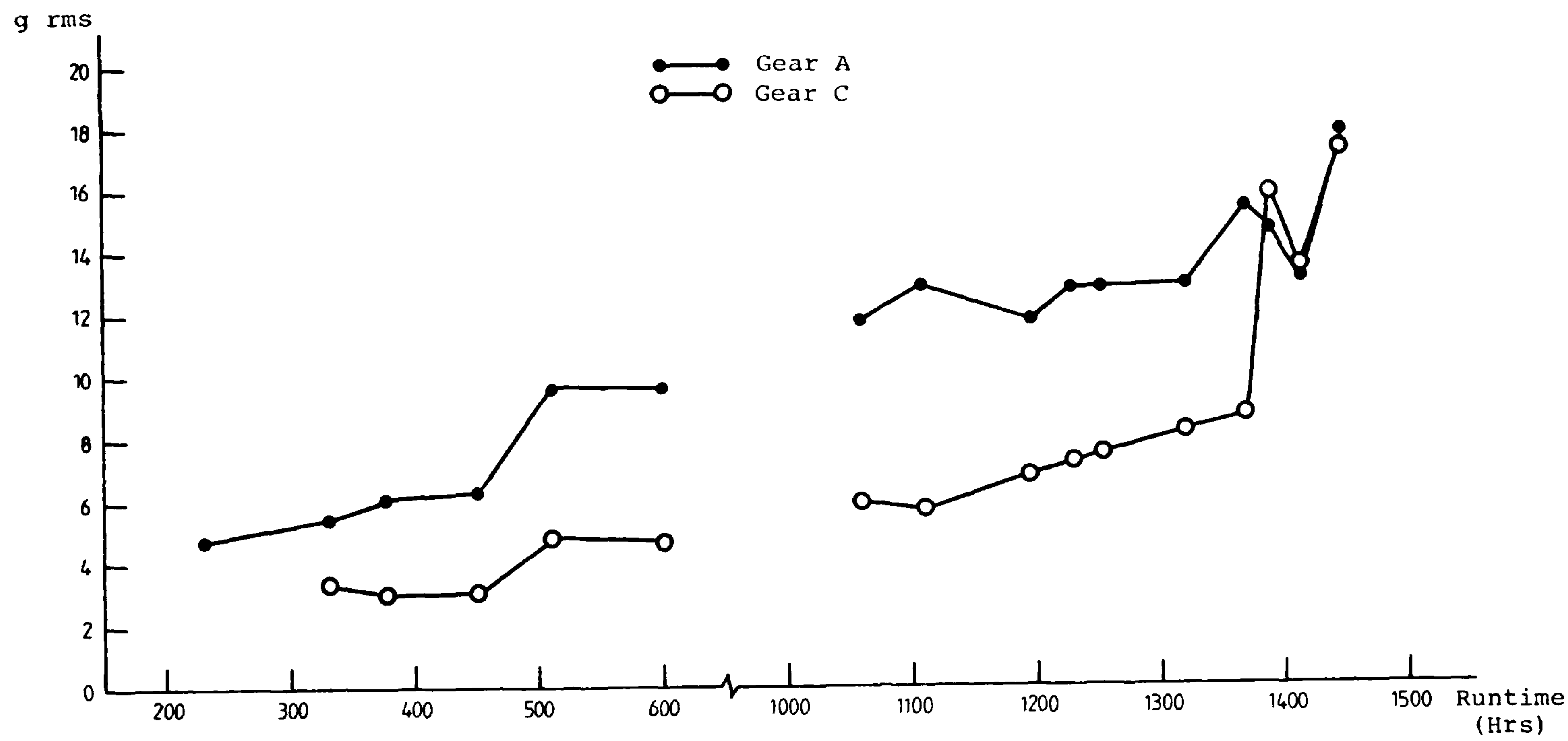
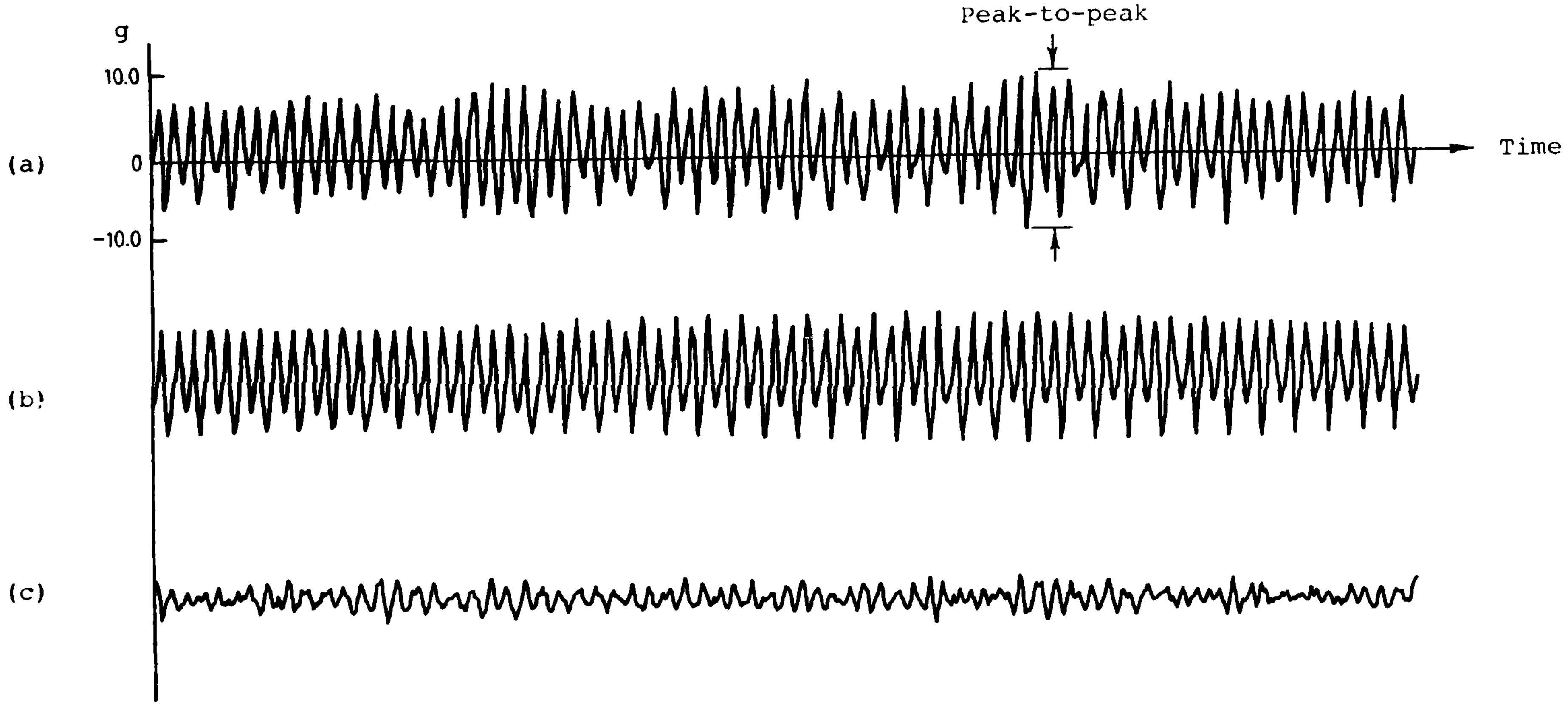


FIG. 4 TOTAL VIBRATION LEVEL



Time scale : 1 cm = 1 ms

FIG. 5 TIME DOMAIN ANALYSIS

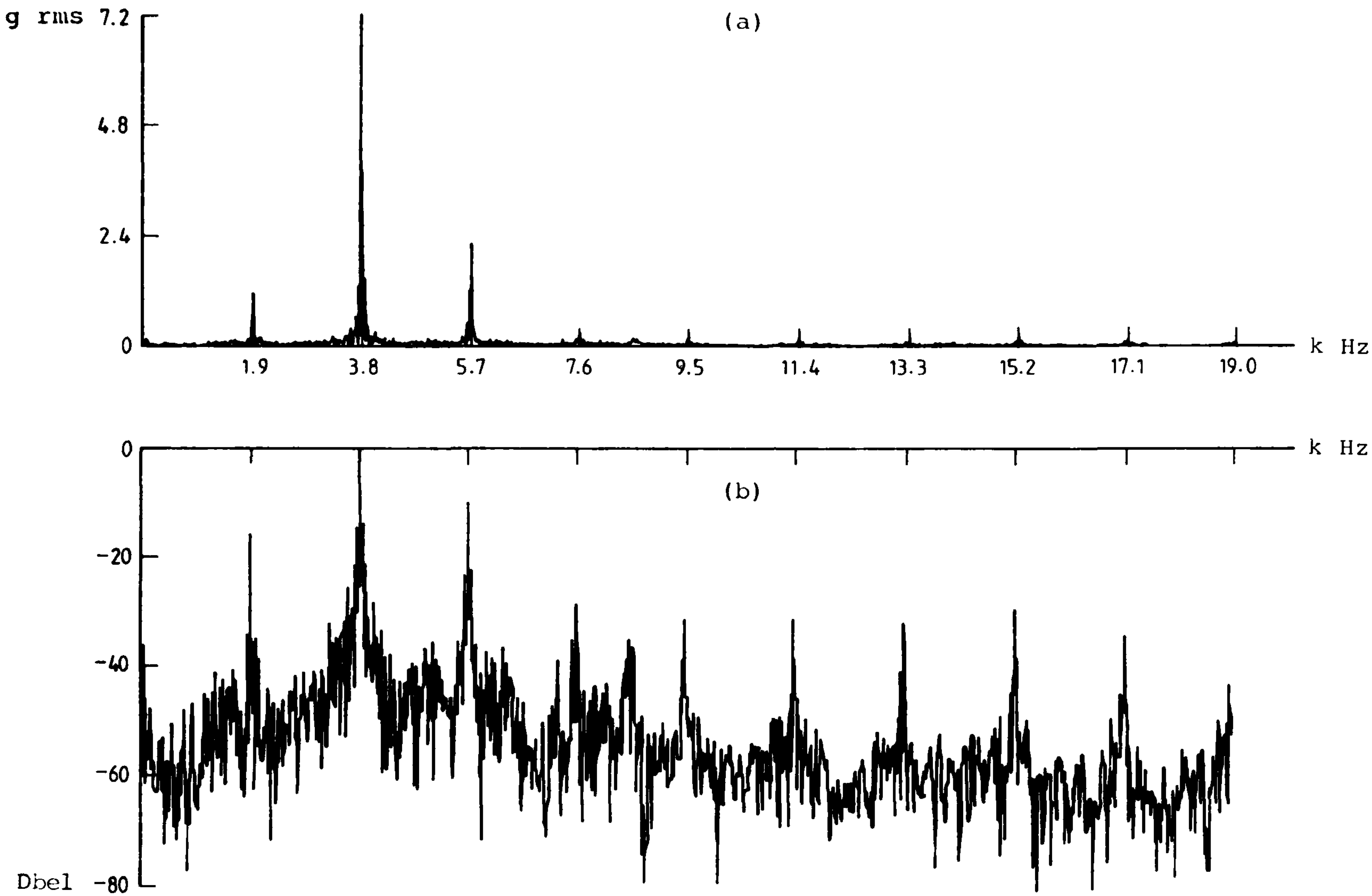


FIG. 6 SPECTRUM OF AVERAGE

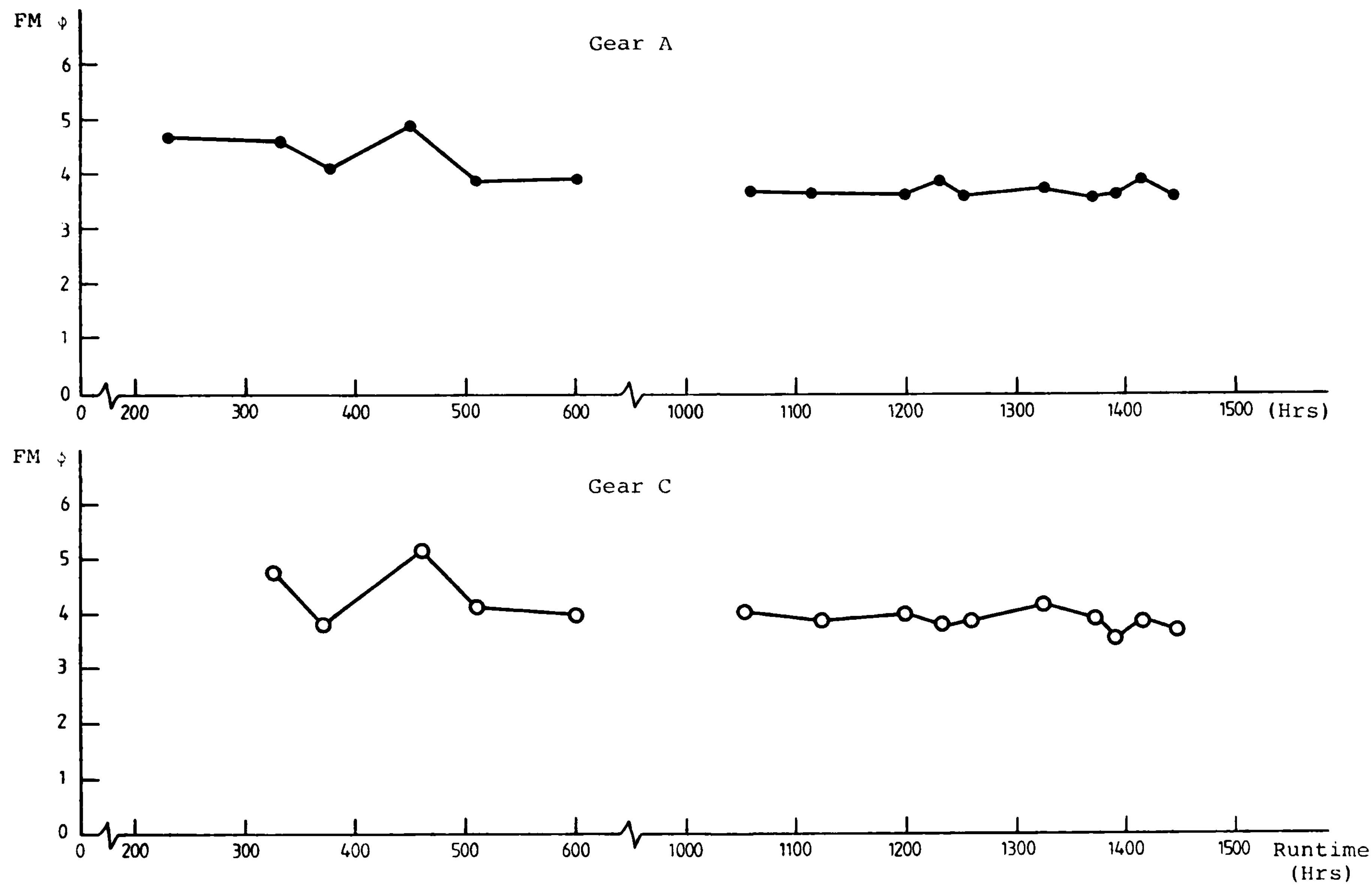


FIG. 7 FM φ ANALYSIS

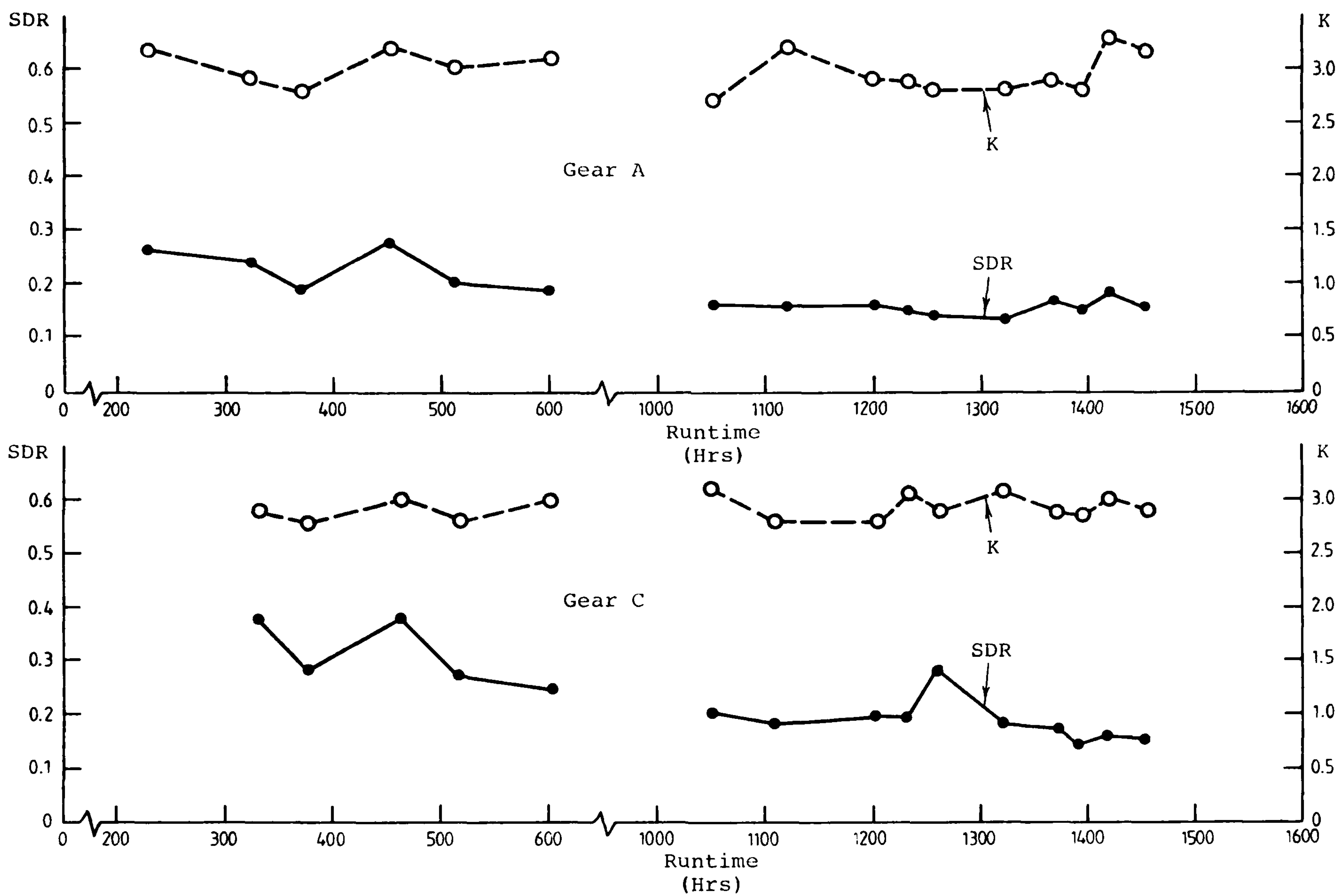


FIG. 8 FM4 ANALYSIS

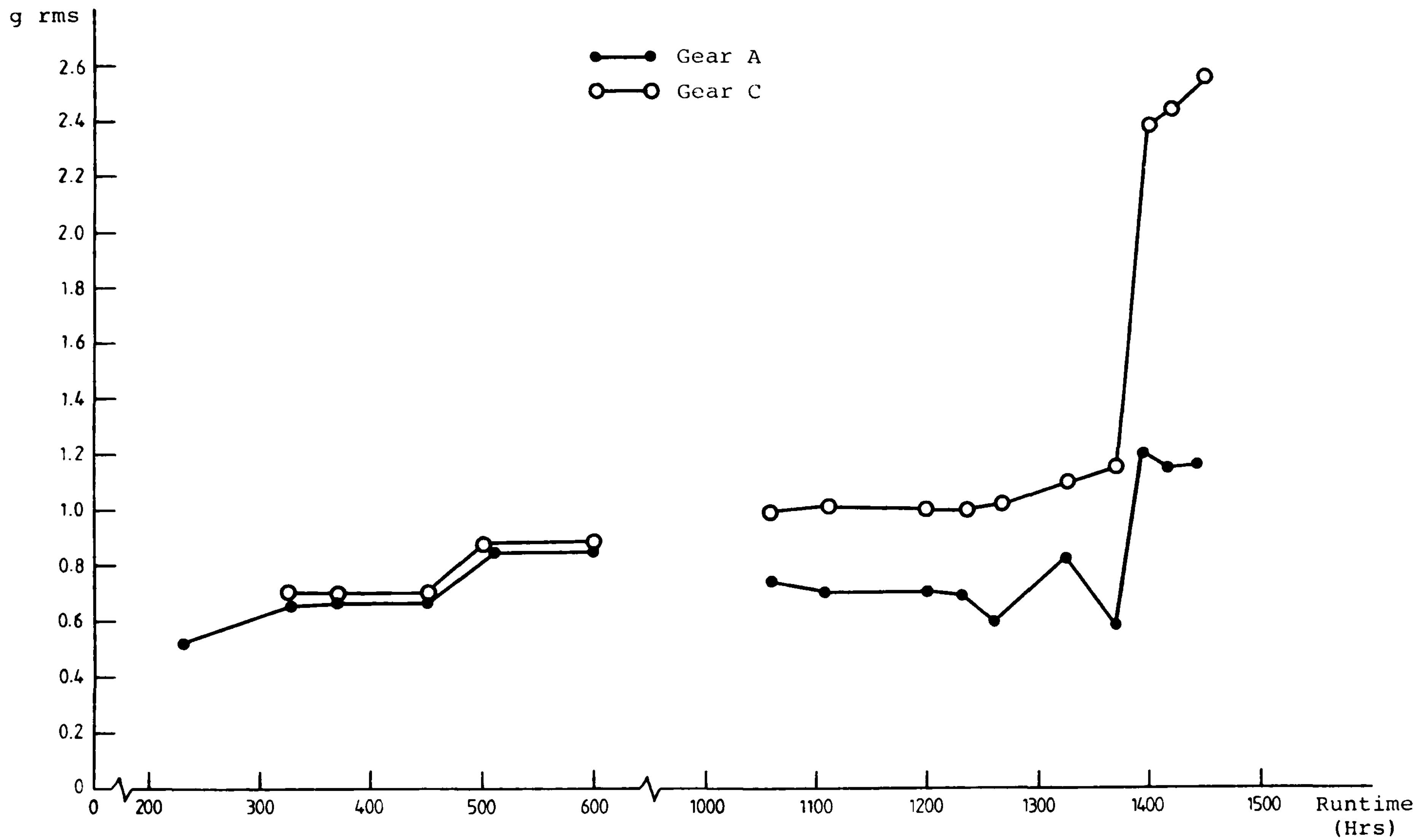


FIG. 9 - FUNDAMENTAL COMPONENT OF MESHING FREQUENCY

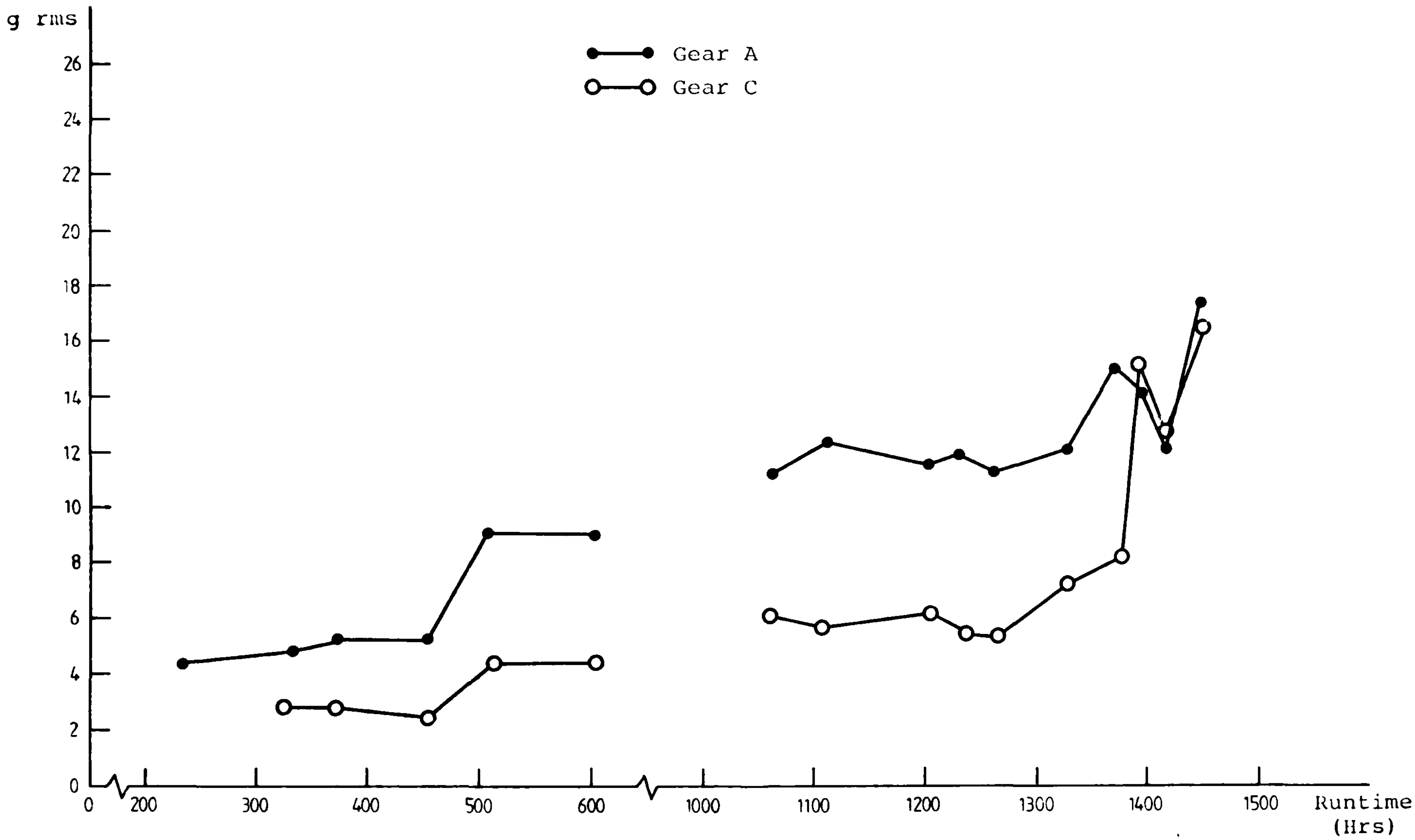


FIG 10. 2ND HARMONIC OF MESHING FREQUENCY

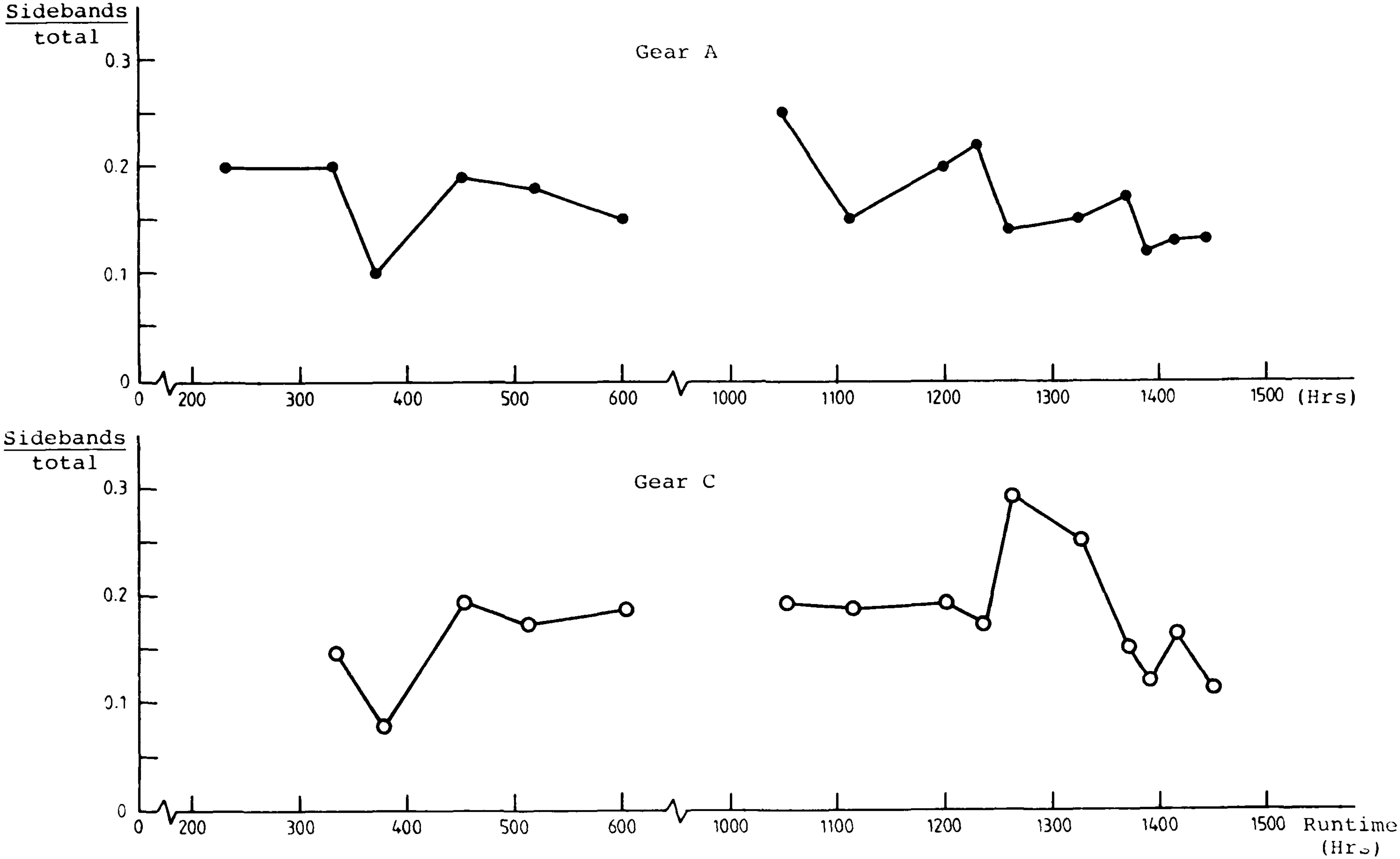


FIG 11. 1ST ORDER SIDEBANDS/TOTAL

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Condition Monitoring Vibration Analysis Gears	21110

16. Abstract

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Results have shown that although heavy wear, in the form of fine pitting and scuffing, occurred over most of the tooth surfaces, the time domain procedures and levels of the fundamental and first harmonic of meshing frequency did not respond to damage to the gears. Total vibration and the ratio of sideband to total energy showed only marginal response to wear.

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